Direct Detection of Exoplanets in the Infrared

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Exoplanet Forum

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1.1 Contributors

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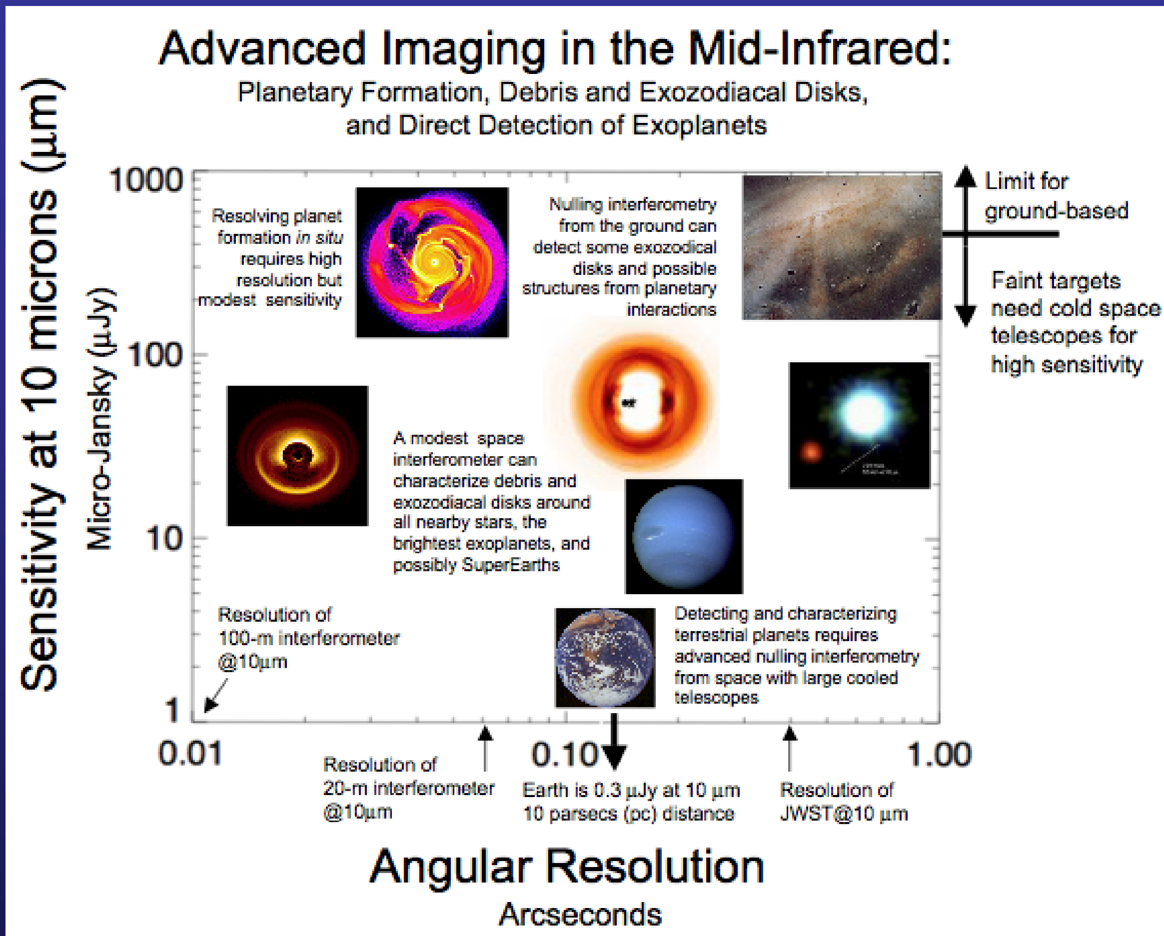
Sensitivity and Resolution in the Mid-IR



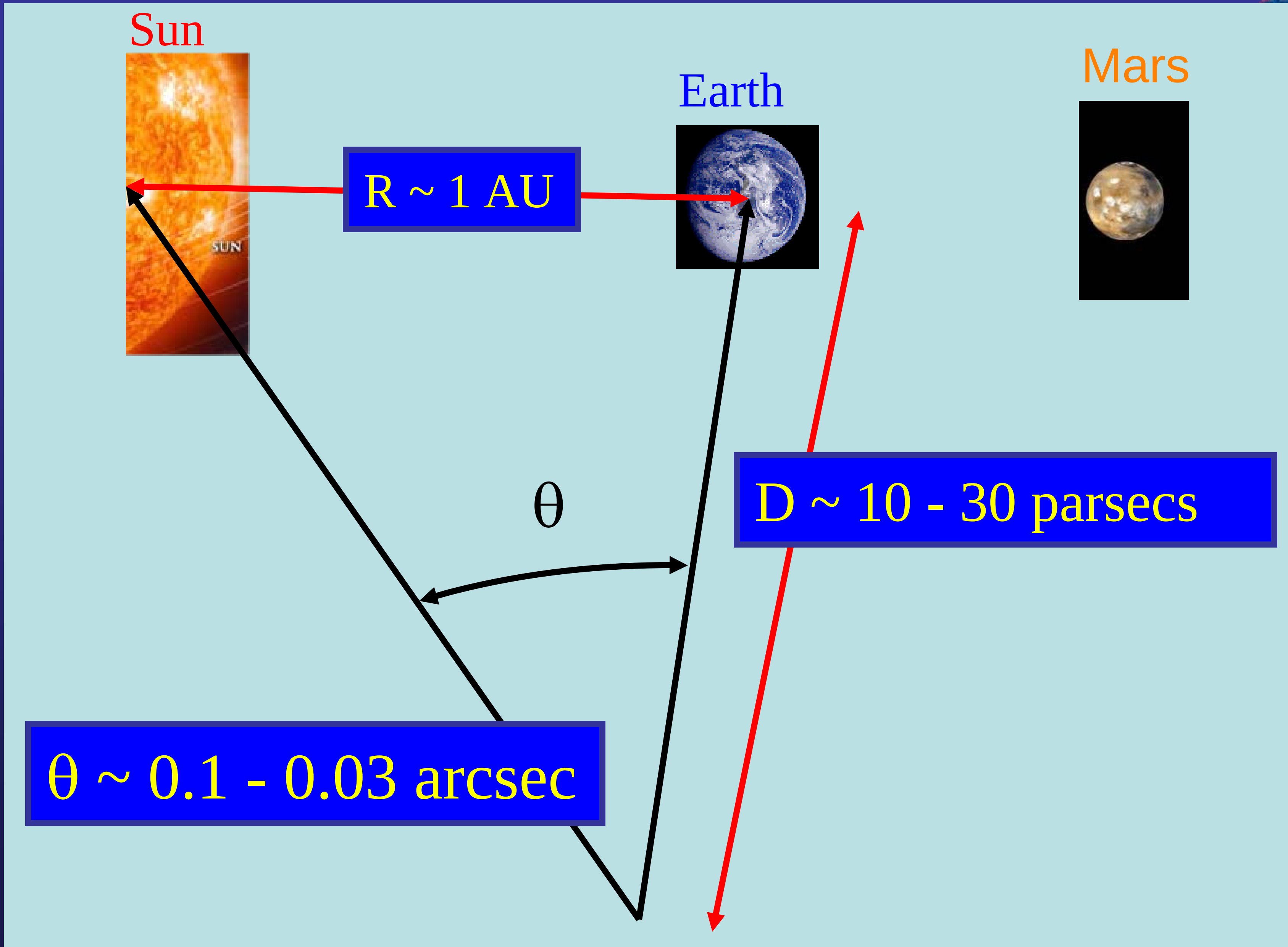
Ground-based interferometry in the IR:

- Limited sensitivity
- Long baselines available
- Good for studying protoplanetary disks

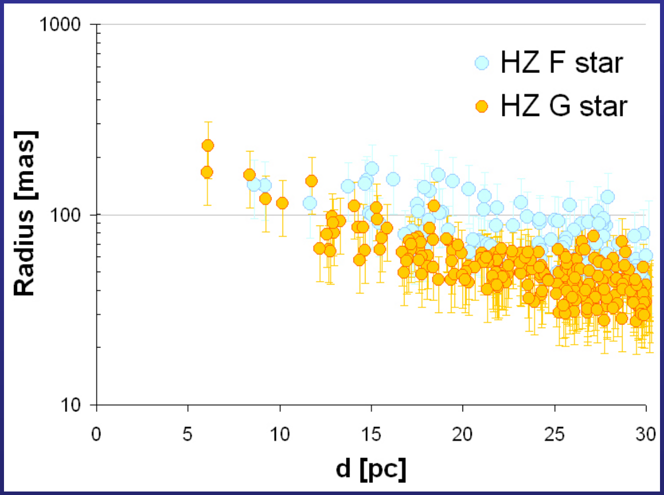
Space-based interferometry:

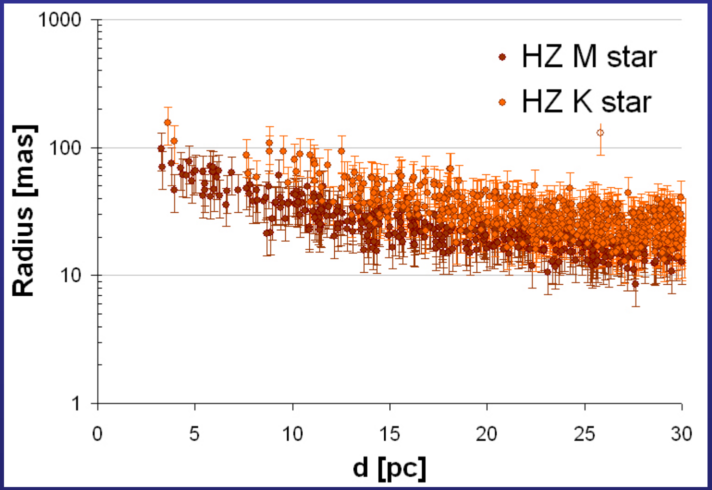
1. Structurally Connected interferometer (limited baseline length)
   - Exozodi levels for ALL TPF/Darwin stars
   - Debris Disks
   - Characterize Warm & Hot Planets & Super Earths
2. Formation-flying or tethers (long baselines)
   - Detect and characterize many Earth-sized planets
   - Transformational astrophysics

Why high angular resolution is needed



Angular Size of the Habitable Zone





Size of habitable zone is 10 < HZ (mas) < 200

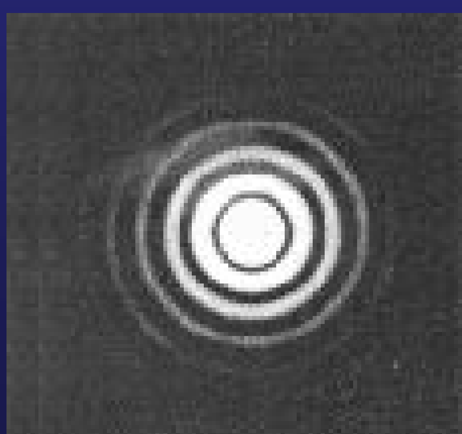
for all F,G,K, M stars < 30 pc from Earth

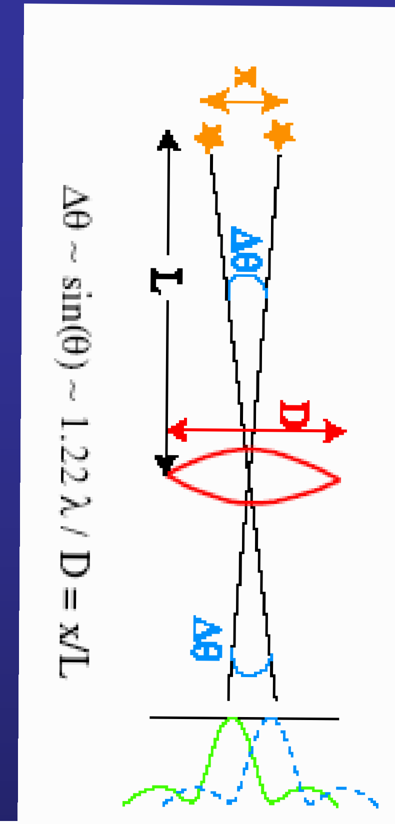
Resolution of a conventional telescope: Rayleigh Criterion

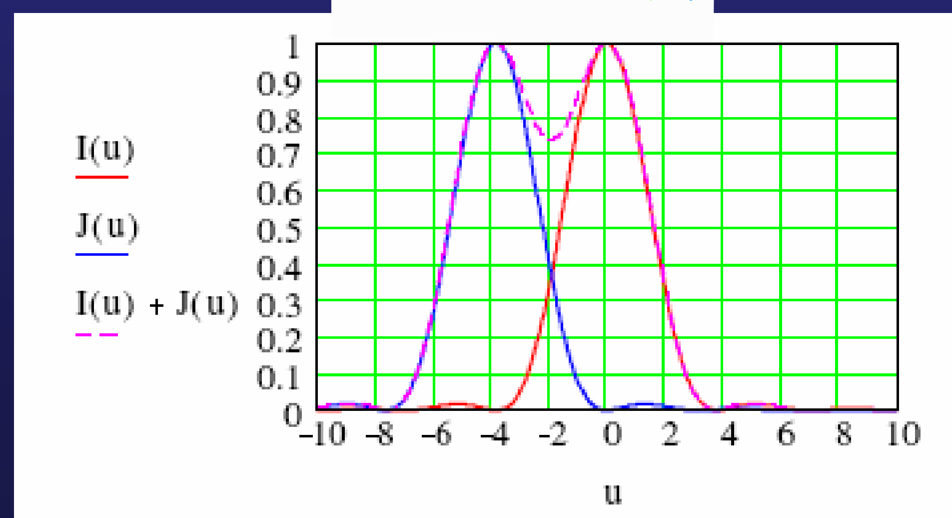
$\Delta\theta \sim 1.22\ \lambda / D$

λ = wavelength of light

D = telescope diameter







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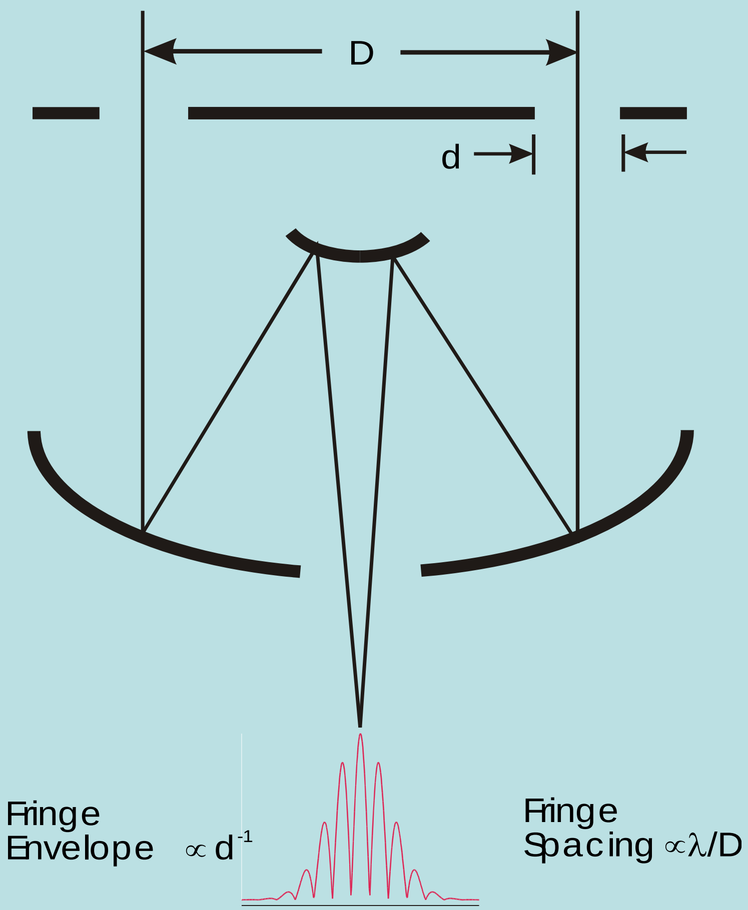
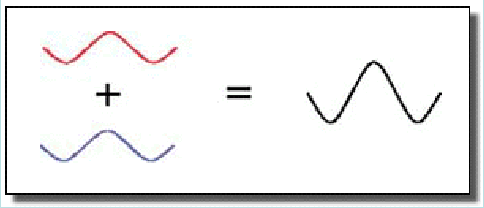
A simple interferometer

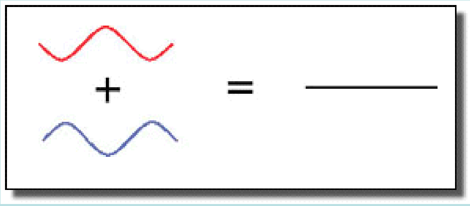
Simplest Interferometer -- Aperture Masking



•You get a peak when pathlengths are equal on both sides -- "white light fringe"



•You get a null when pathlengths differ by one half a wavelength -- a "dark fringe"



Interferometer Resolution

Interferometer Resolution is:

$\lambda/(2B)$ where λ is wavelength and B is the baseline.

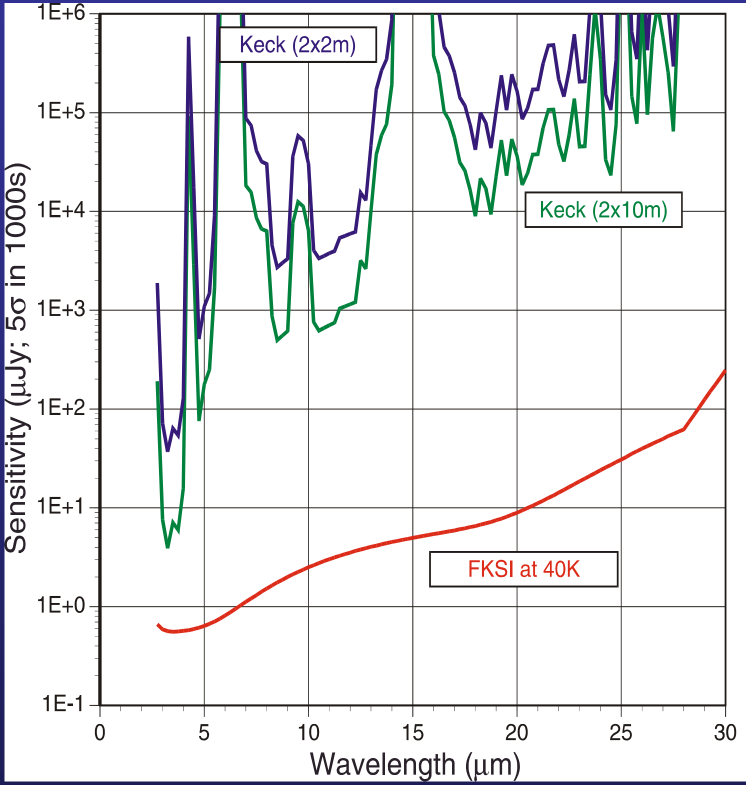
For 0.1 mas resolution --> B = 10 m at 10 μm

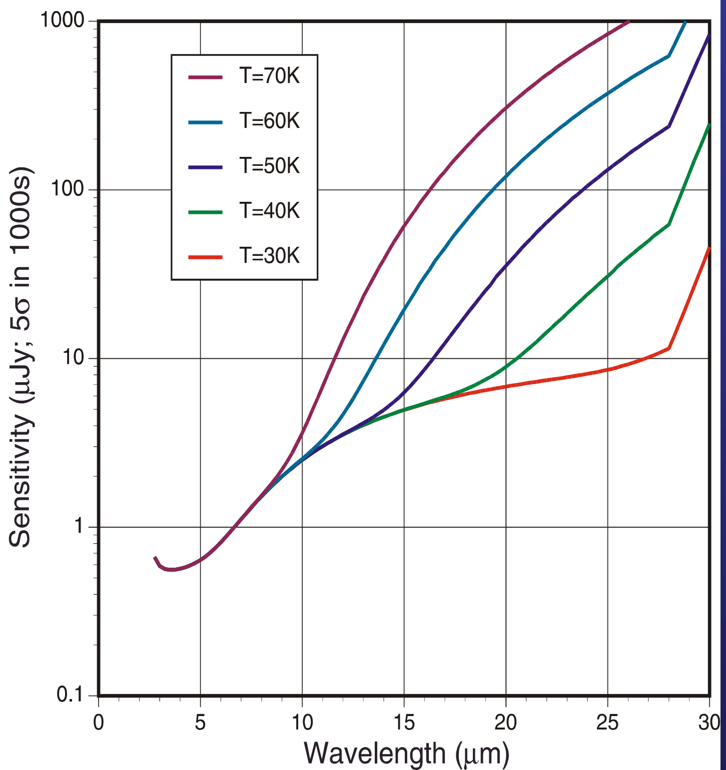
0.01 mas resolution --> B = 100 m at 10 μm

This sets the minimum baseline size.

A 20-40 m baseline at 10 μm is adequate resolution for a substantial number of nearby F,G,K, stars, or 1/2 that if the center wavelength is 5 μm.

A SMALL Cooled Space Telescope is Very Sensitive Compared to a LARGE Ground-based Telescope

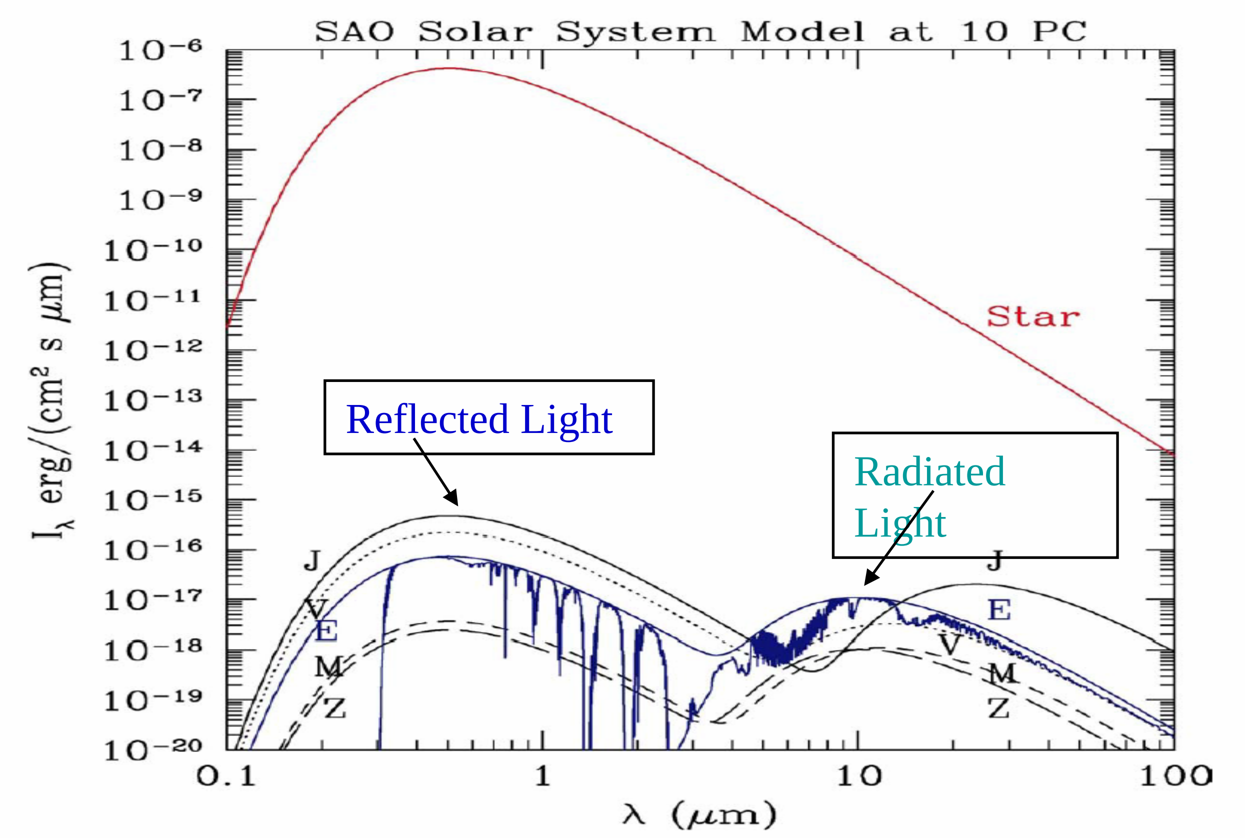




Left panel . The sensitivity of the FKSI system (1 m telescopes) with telescope temperature at 40 K compared to either two 10 m Keck telescopes or two Keck 2 m outrigger telescopes.
Right panel. Effect of telescope temperature on FKSI sensitivity.

The Solar System Viewed from 10 pc

You can search for planets directly either from *reflected* starlight or *re-radiated* starlight

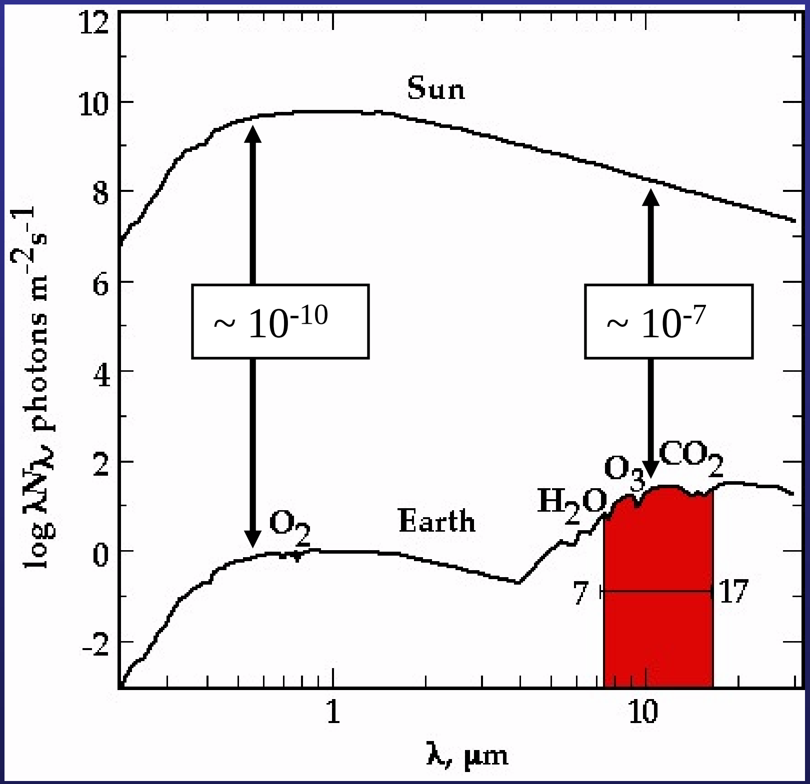


Notice that *different planets* have *different spectra* in the infrared

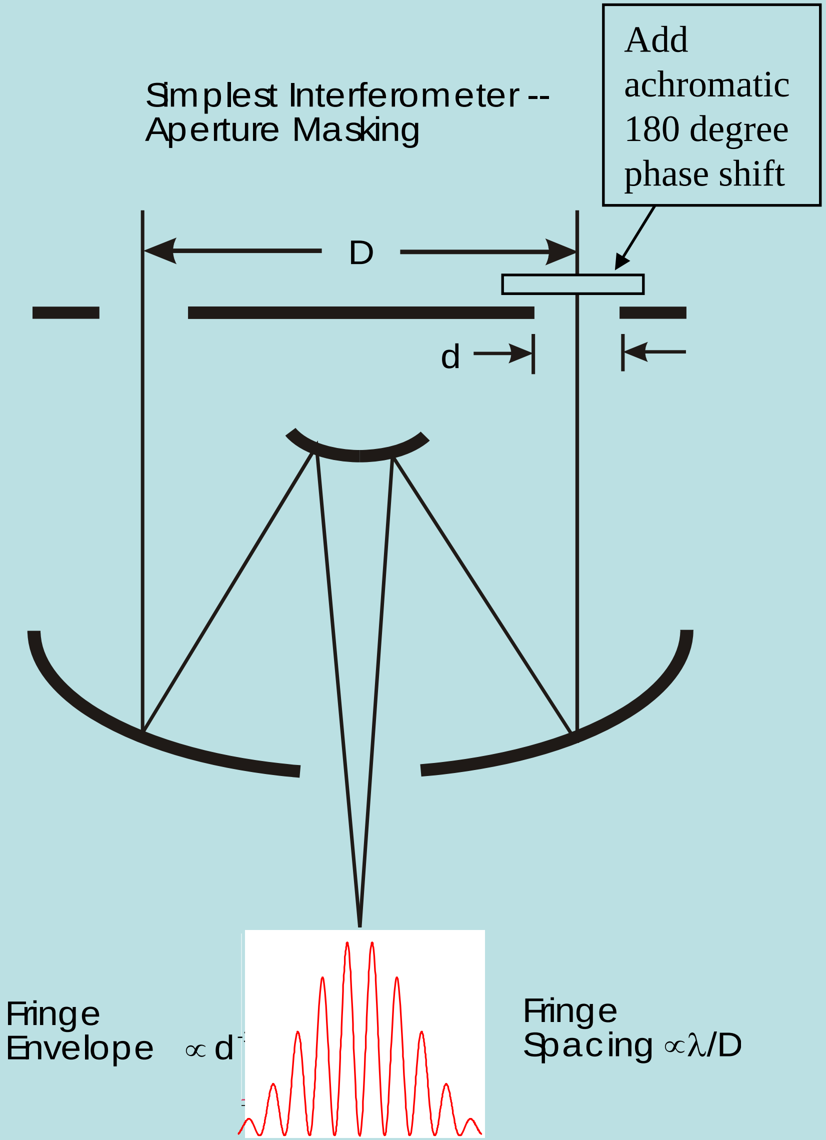
DesMarais et al. (2002)

Detecting Earth-size Planets is Difficult

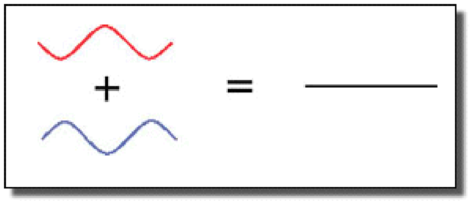
- Detecting light from planets beyond solar system is hard:
  - Earth sized planet emits few photons/sec/m^2 at 10 μm
  - Parent star emits 10^6 more
  - Planet within 1 AU of star
  - Dust in target solar system $\times$300 brighter than planet



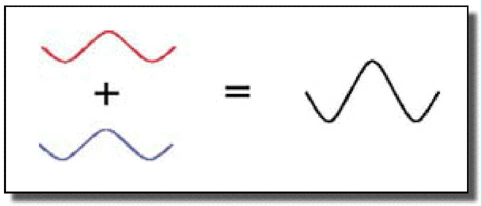
A simple nulling interferometer



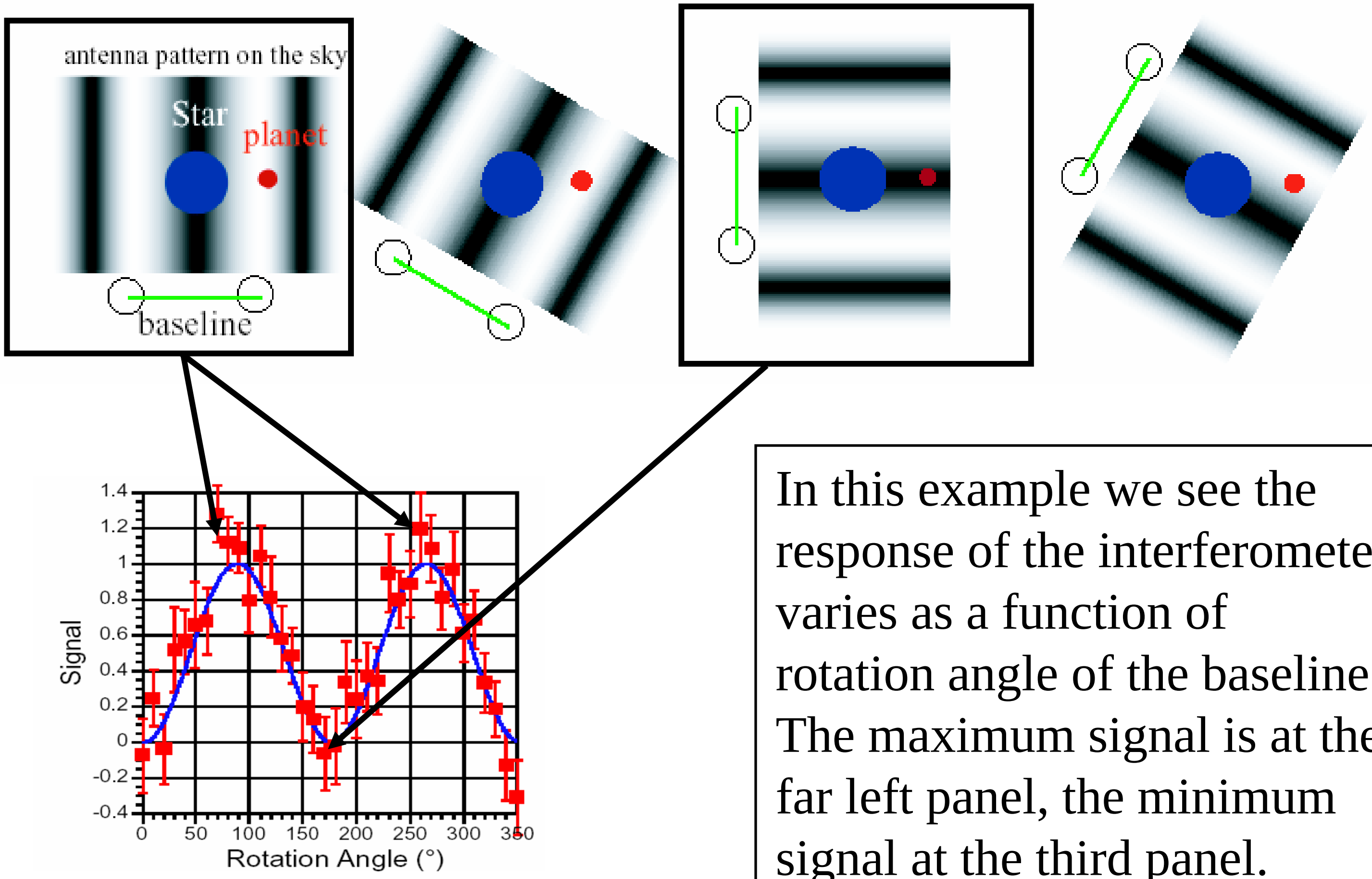
•You get a null when pathlengths are equal on both sides -- “white light null fringe”



•You get a peak when pathlengths differ by one half wavelength -- a “bright fringe”

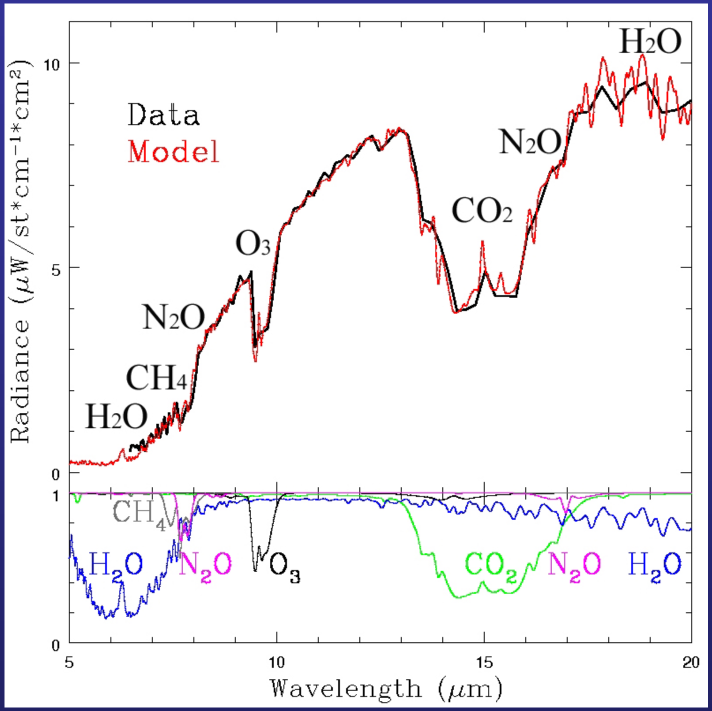


A Simple Example of an Interferometric Detection of a Planet



In this example we see the response of the interferometer varies as a function of rotation angle of the baseline. The maximum signal is at the far left panel, the minimum signal at the third panel.

Earth Spectrum



Earth's spectrum shows absorption features from many species, including ozone, nitrous oxide, water vapor, carbon dioxide, and methane

Biosignatures are molecules out of equilibrium such as oxygen, ozone, and methane or nitrous oxide.

Spectroscopy with R~50 is adequate to resolve these features.

Observations and some findings

•Advanced imaging with both high-angular resolution and high sensitivity in the mid-infrared is essential for future progress across all major fields of astronomy.

•Exoplanet studies particularly benefit from these capabilities.

•Thermal emission from the atmospheric and telescope(s) limits the sensitivity of ground-based observations, driving most science programs towards space platforms.

•Even very modest sized cooled apertures can have orders of magnitude more sensitivity in the thermal infrared than the largest ground-based telescopes currently in operation or planned.

•We find a mid-IR interferometer with a nulling (coronagraphic) capability on the ground and a connected-element space interferometer both enable transformative science while laying the engineering groundwork for a future "Terrestrial Planet Finder" space observatory requiring formation-flying elements.

Ground-based interferometry

Keck Interferometer

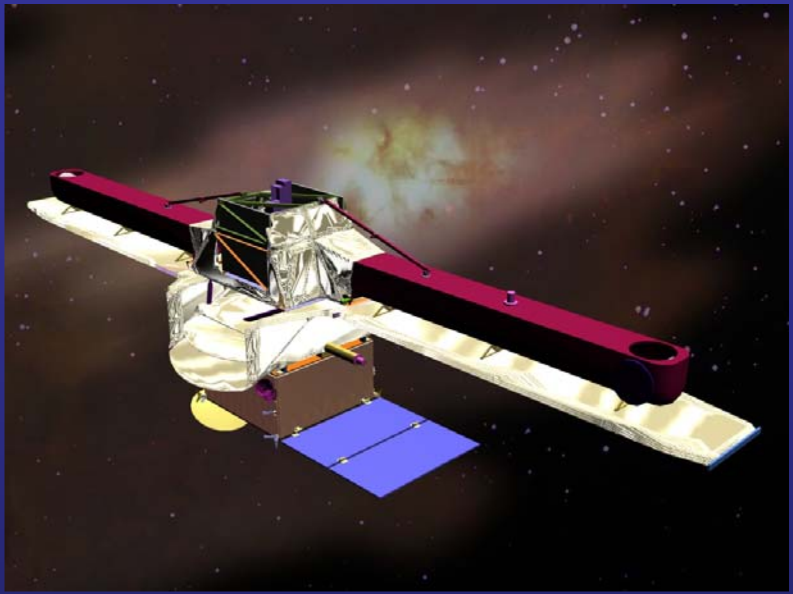
- •Protoplanetary disk studies (T Tauri & Herbig Ae/Be stars)
- •Debris Disks Around Nearby Stars (Key Science Projects) with limits around 100-200 Solar System Zodis

Large Binocular Telescope Interferometer

- •Debris Disks with lower limits ~30 Solar System Zodis

These projects have been essential to the development of the nulling technique and they will produce important near-term results.

A Small Structurally Connected Interferometer; The Fourier-Kelvin Stellar Interferometer (FKSI) Mission



PI: Dr. William C. Danchi

Exoplanets & Stellar Astrophysics, Code 667
NASA Goddard Space Flight Center

Technologies:

- Infrared space interferometry
- Large cryogenic infrared optics
- Passive cooling of large optics
- Mid-infrared detectors
- Precision cryo-mechanisms and metrology
- Precision pointing and control
- Active and passive vibration isolation and mitigation

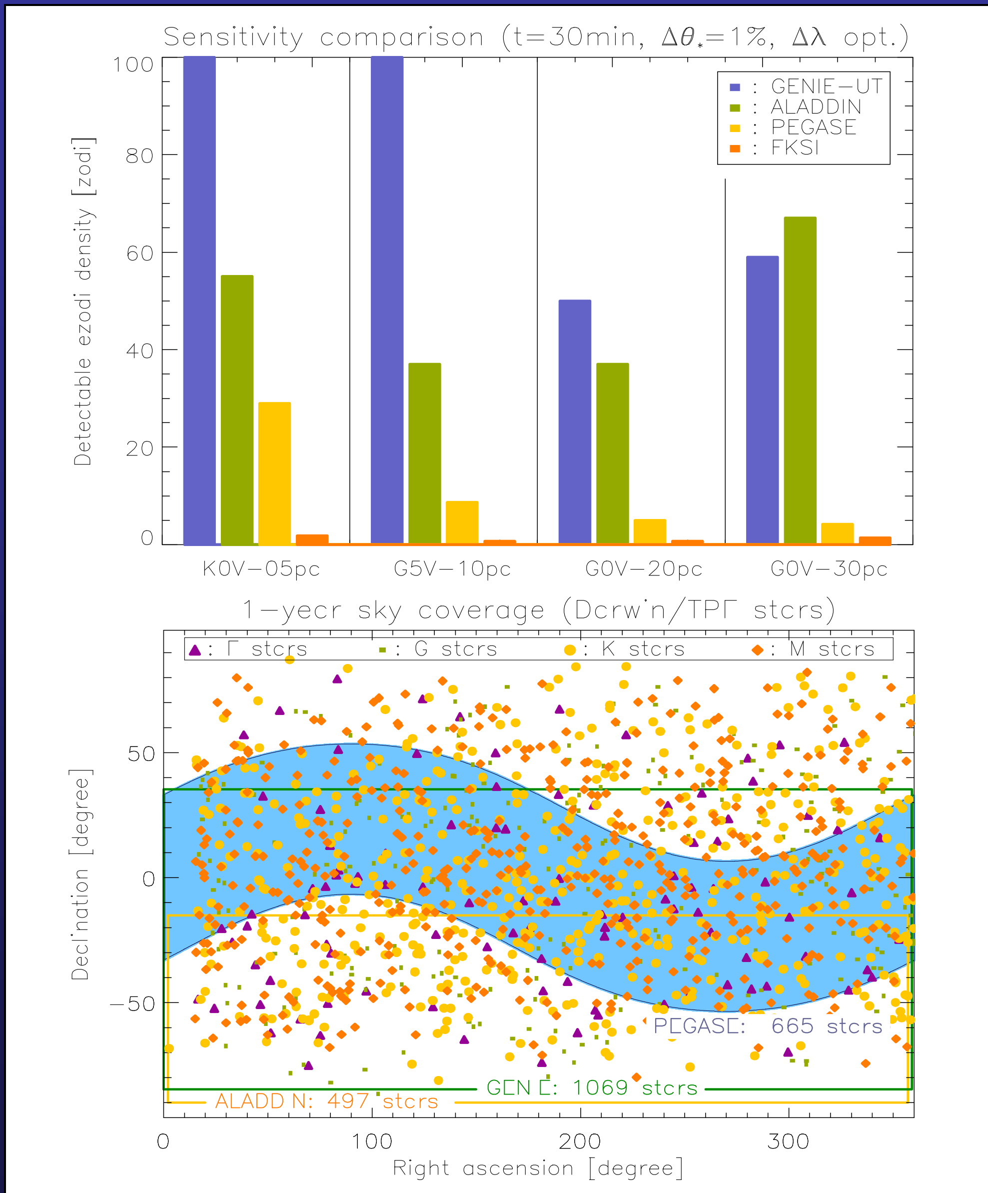
Key Science Goals:

- **Observe Circumstellar Material**
  - Exozodi measurements of nearby stars and search for companions
  - Debris disks, looking for clumpiness due to planets
- **Detect >20 Extra-solar Giant Planets**
  - Characterize atmospheres with R=20 spectroscopy
  - Observe secular changes in spectrum
  - Observe orbit of the planet
  - Estimate density of planet, determine if rocky or gaseous
  - Determine main constituents of atmospheres
- **Star formation**
  - Evolution of circumstellar disks, morphology, gaps, rings, etc.
- **Extragalactic astronomy**
  - AGN nuclei

Key Features of Design:

- ~0.5 m diameter aperture telescopes
- Passively cooled (<70K)
- 12.5 m baseline
- 3 – 8 (or 10 TBR) micron science band
- 0.6-2 micron band for precision fringe and angle tracking
- Null depth better than 10^-4 (floor), 10^-5 (goal)
- R=20 spectroscopy on nulled and bright outputs of science beam combiner

Debris Disk Sensitivity



Expected performance for Pegase and FKSI compared to the ground-based instruments (for 30 min integration time and 1% uncertainty on the stellar angular diameters).

Sky coverage after 1 year of observation of GENIE (dark frame), ALADDIN (light frame) and Pegase (shaded area) shown with the Darwin/TPF all sky target catalogue. The blue-shaded area shows the sky coverage of a space-based instrument with an ecliptic latitude in the [-30˚, 30˚] range (such as Pegase). The sky coverage of FKSI is similar to that of Pegase with an extension of 40˚ instead of 60˚

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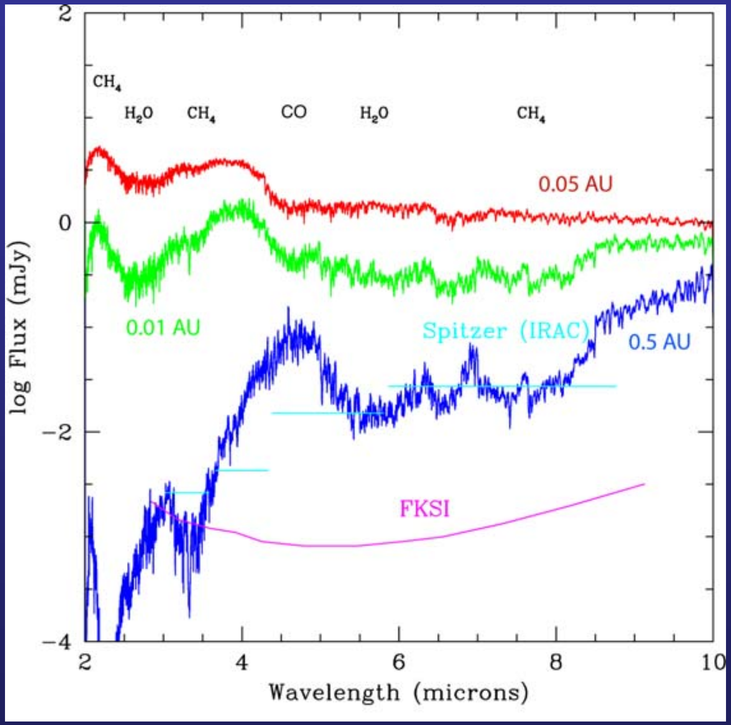
Exoplanet Characterization with a Small Structurally Connected Interferometer

Orbital Parameters	What FKSI does:
Removes sin(I) ambiguity	Measure
Planet Characteristics	
Temperature	Measure
Temperature variability due to distance changes	Measure
Planet radius	Measure
Planet mass	Estimate
Planet albedo	Cooperative
Surface gravity	Cooperative
Atmospheric and surface composition	Measure
Time variability of composition	Measure
Presence of water	Measure
Solar System Characteristics	
Influence of other planets, orbit coplanarity	Estimate
Comets, asteriods, zodiacal dust	Measure



Left panel. Characteristics of exoplanets that can be measured using FKSI. (b) Right panel. The FKSI system can measure the spectra of exoplanets with a wide range of semi-major axes.

Findings Concerning the Performance of a Small Structurally Connected Interferometer

- *To date, progress has been made on the physical characteristics of planets largely through transiting systems, but a small planet finding interferometer can measure the emission spectra of a large number of the non-transiting ones, as well as more precise spectra of the transiting ones.*

- *As a conservative estimate, we expect that a small system could detect (e.g. remove the sin(i) ambiguity) and characterize about 75-100 known exoplanets.*

- *A small mission is ideal for the detection and characterization of exozodiacal and debris disks around ALL TPF candidate stars in the Solar neighborhood*

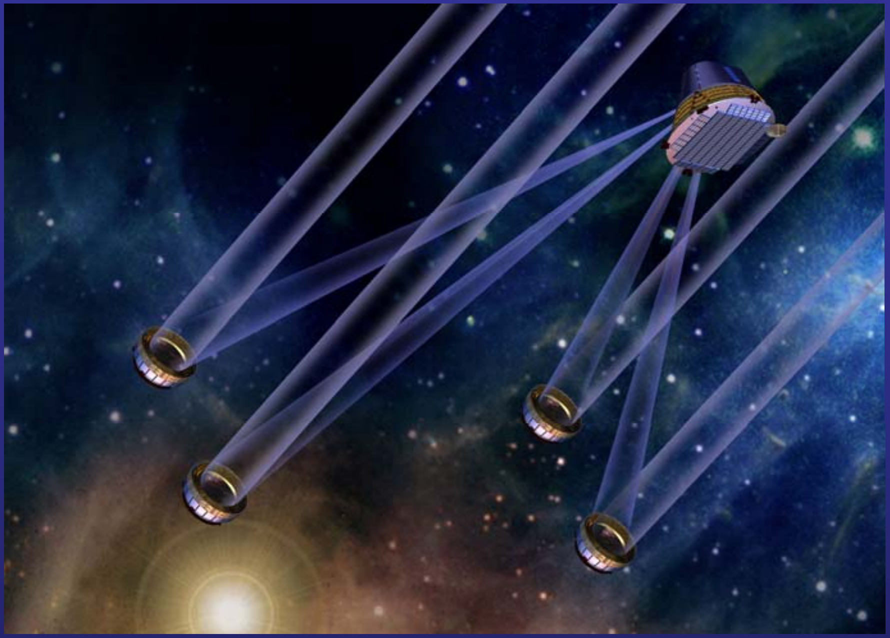
- *If the telescopes are somewhat larger than has been discussed in some of the existing mission concepts (e.g., 1-2 m) and are somewhat cooler (e.g., < 60K) so that the system can operate at longer wavelengths, it is possible for a small infrared structurally-connected interferometer to detect and characterize super-earths and even ~50-75 earth-sized planets around the nearest stars.*

- ***Further studies of the capabilities of a small infrared structurally-connected interferometer are necessary to improve upon our estimates of system performance***

Flagship Mission Requirement Summary

Flagship Interferometer Mission Requirement Summary	
Star Types	F, G, K, selected, nearby M, and others
Habitable Zone	0.7Š1.5 (1.8) AU scaled as $L^{1/2}$ *(Note *)*
Number of Stars to Search	>150
Completeness for Each Core Star	90%
Minimum Number of Visits per Target	3
Minimum Planet Size	0.5Š1.0 Earth Area
Geometric Albedo	EarthÕs
Spectral Range and Resolution	6.5Š18 [20] μ m; R = 25 [50]
Characterization Completeness	Spectra of 50% of Detected or 10 Planets Maximum
Giant Planets	Jupiter Flux, 5 AU, 50% of Stars
Maximum Tolerable Exozodiacal Emission	10 times Solar System Zodiacal Cloud
*There are two definitions in the literature for the outer limit of the habitable zone. The first is 1.5 AU scaled to the luminosity to the ½power based on Kasting et al. (1993). The second is 1.8 AU scaled in the same way from Forget & Pierrehumbert (1997).	

Terrestrial Planet Finder Interferometer



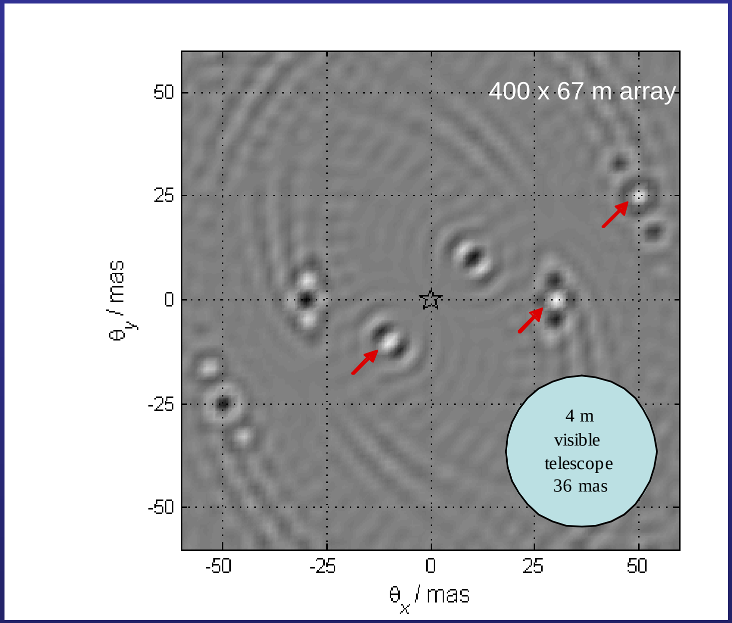
Salient Features

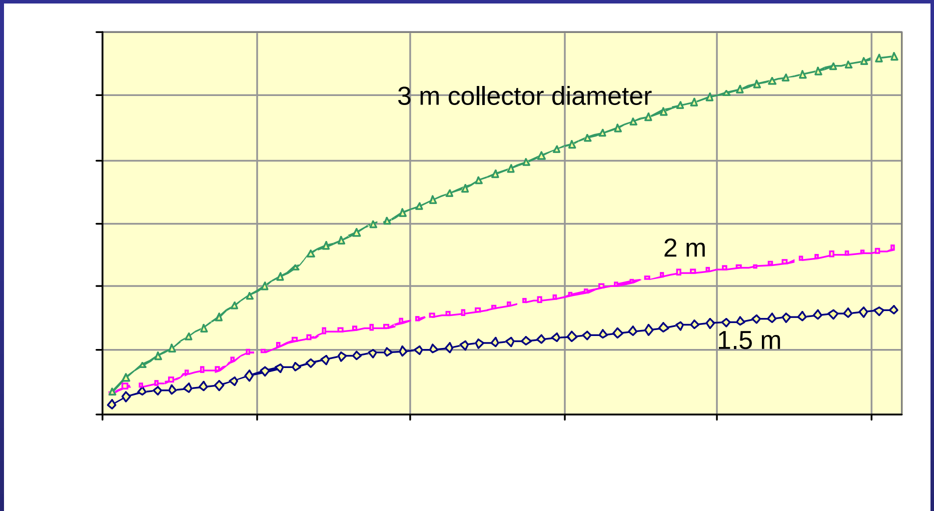
- Formation Flying Mid-IR nulling Interferometer
- Starlight suppression to and 10^{-5} (mid-IR)
- Heavy launch vehicles
- L2 baseline orbit
- 5 year mission life (10 year goal)
- Potential collaboration with European Space Agency

Science Goals

- Detect as many as possible Earth-like planets in the “habitable zone” of nearby stars via their reflected light or thermal emission
- Characterize physical properties of detected Earth-like planets (size, orbital parameters, albedo, presence of atmosphere) and make low resolution spectral observations looking for evidence of a *habitable* planet and bio-markers such as O_2, O_3, CO_2, CH_4 and H_2O
- Detect and characterize the components of nearby planetary systems including disks, terrestrial planets, giant planets and multiple planet systems
- Perform general astrophysics investigations as capability and time permit

TPF Performance Summary

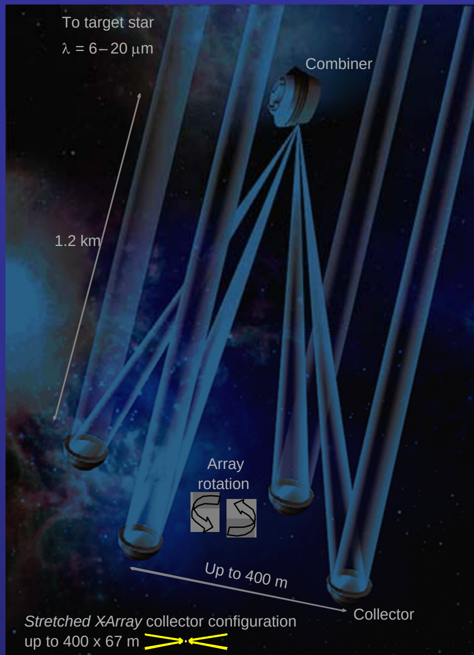




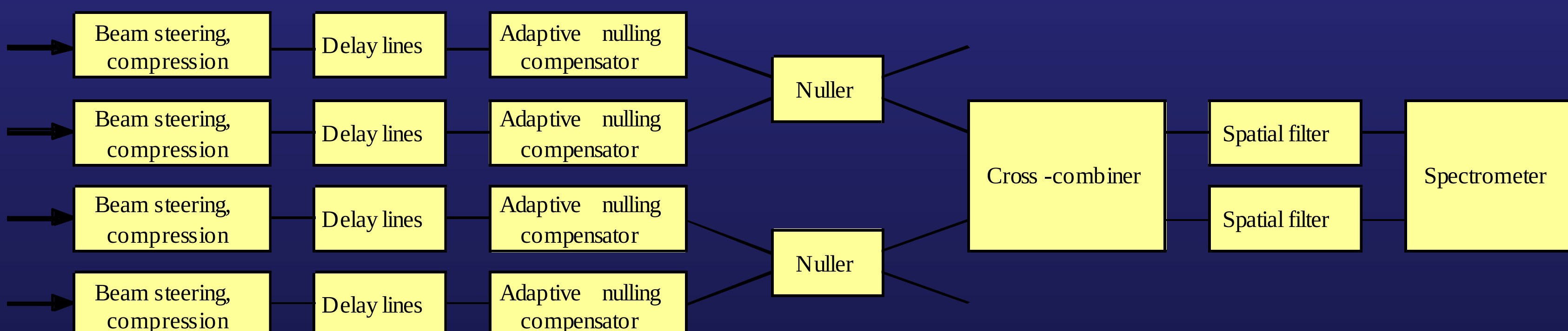
Simulated ‘dirty’ image from Emma X-Array, prior to deconvolution. Angular resolution is 2.5 mas. Planet locations are indicated by red arrows.

Predicted number of Earths detectable by Emma X-Array architecture as a function of elapsed mission time and collector diameter

TPF Architecture



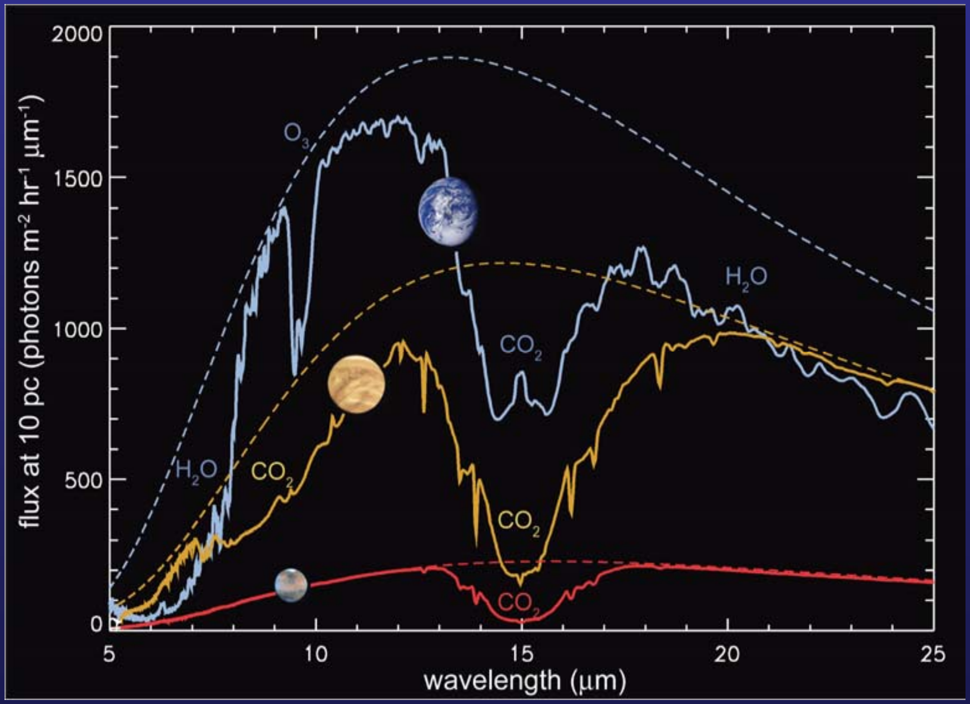
Emma X-Array Architecture resulted from detailed studies of the past several years



Schematic of beam combiner optics

Technology for a Mid-IR Interferometer

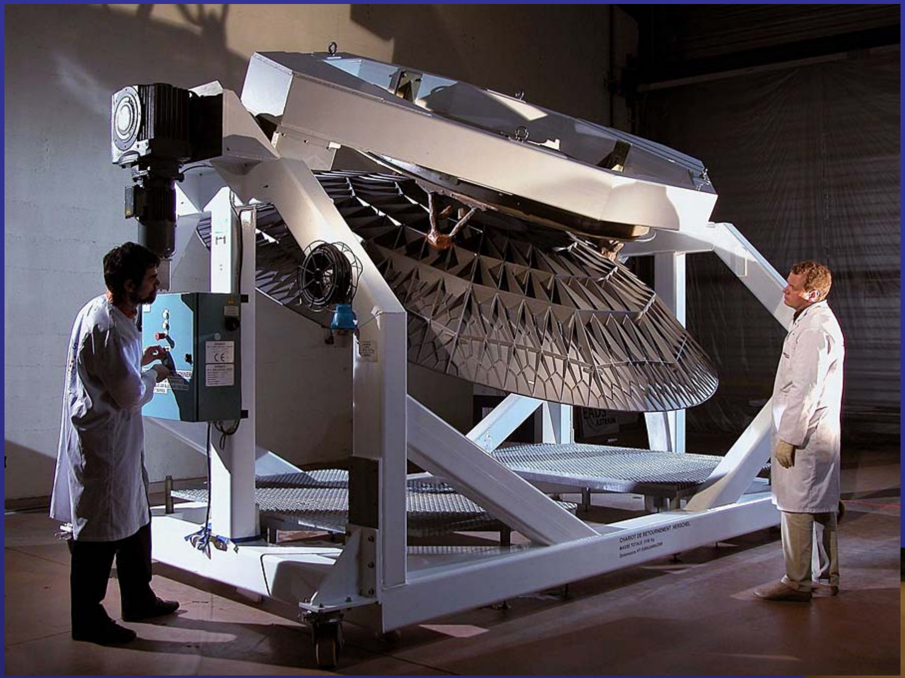
- Science Requirements
- Architecture trade studies



- Starlight suppression
  - Null depth & bandwidth
  - Null stability
- Formation flying
  - Formation control
  - Formation sensing
  - Propulsion systems
- Cryogenic systems
  - Active components
  - Cryogenic structures
  - Passive cooling
  - Cryocoolers
- Integrated Modeling
  - Model validation and testbeds

Single-Aperture Technology

Large Light-Weight Optics

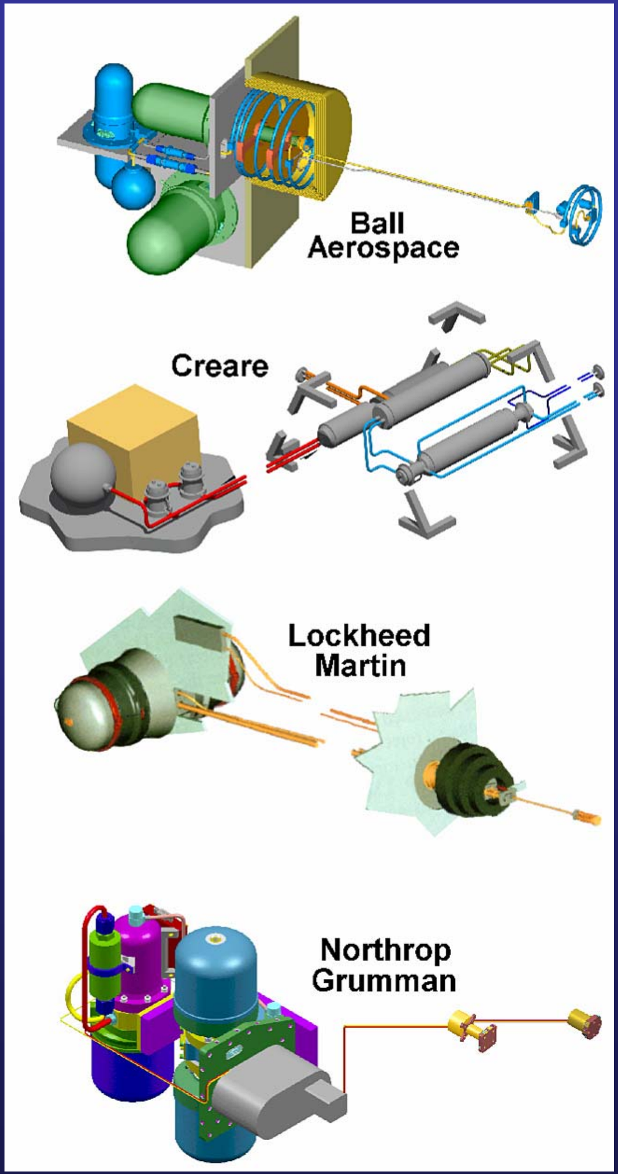


- Herschel Primary Mirror

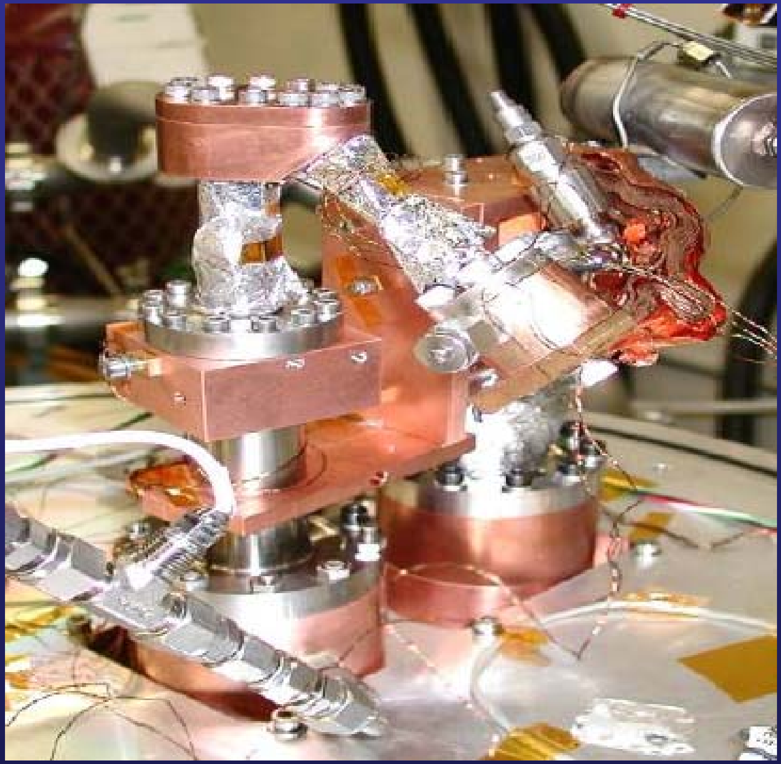
Passive Cryogenic Cooling

- JWST Sunshield

Cryocoolers



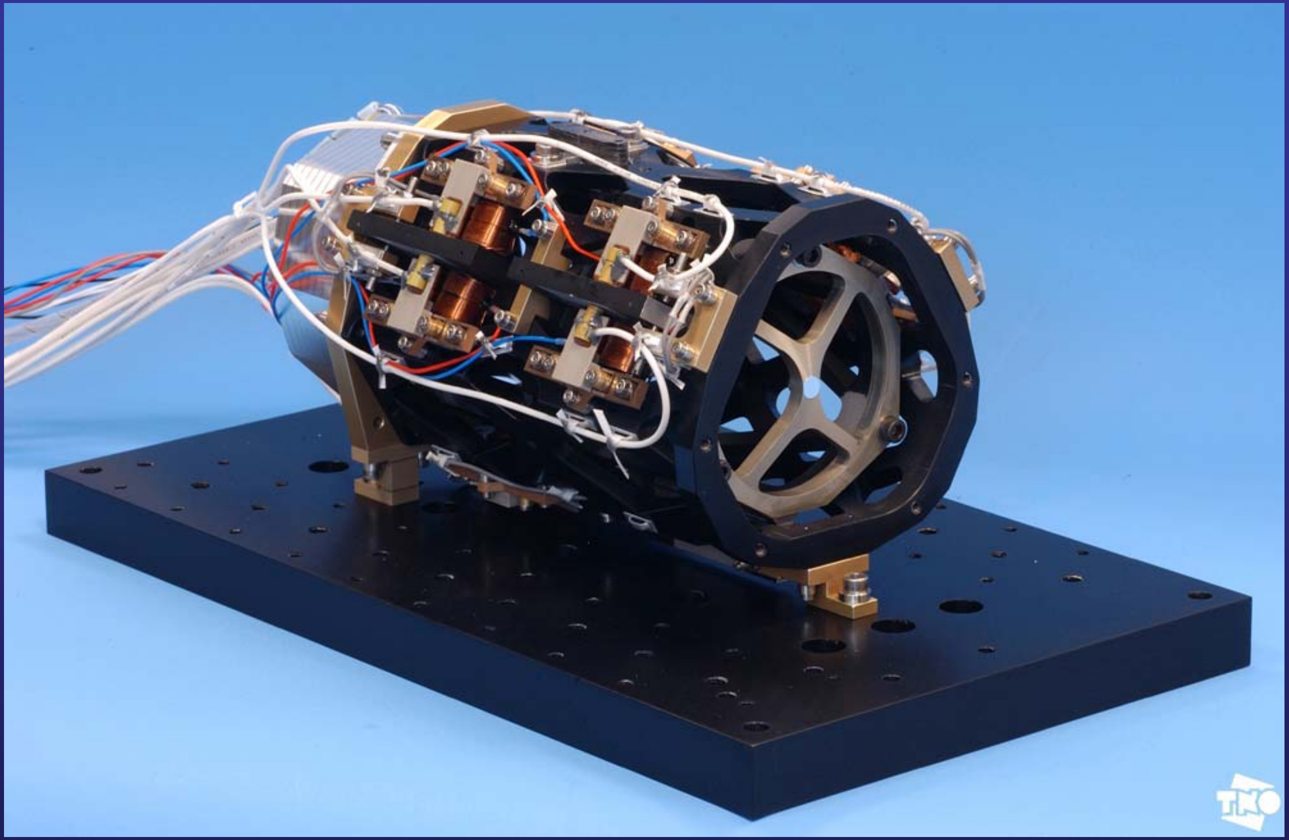
- Advanced Cryocooler Technology Development Program



- JWST Cryocooler (NGST)

Multi-Aperture Technology

Cryogenic Optical Path Compensation

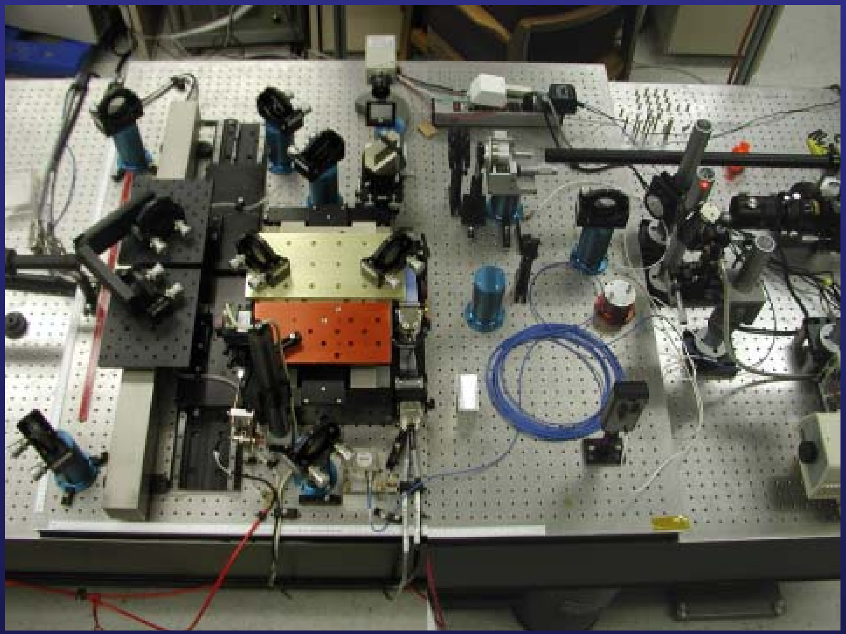


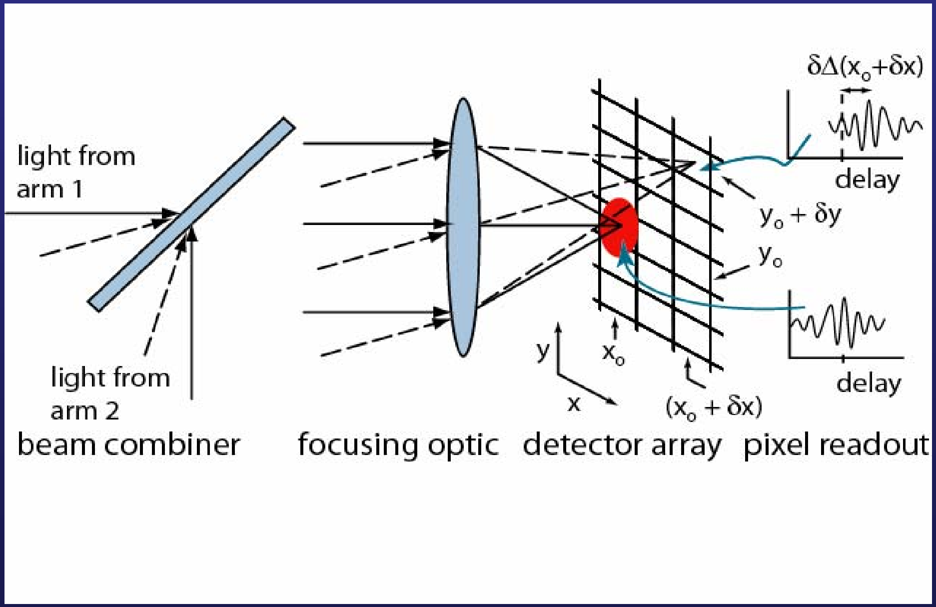
- Prototype delay line for Darwin (ESA)

Wide-Field "Double Fourier" Interferometry in the Lab

The **Wide-field Imaging Interferometry Testbed (WIIT)** was built to develop a wide field-of-view optical/IR imaging interferometry technique

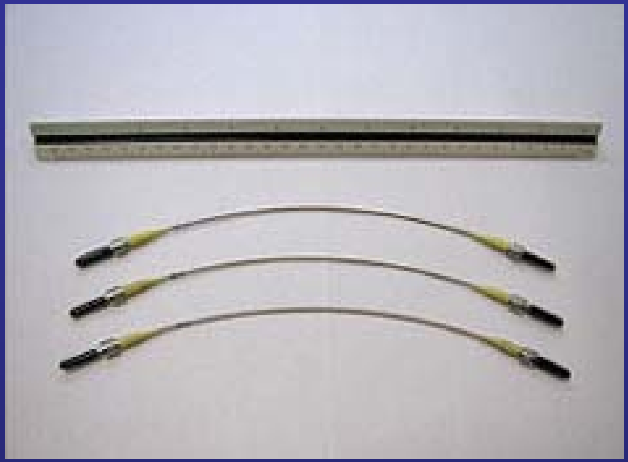
A detector array is substituted for the single-pixel detector used in a conventional Michelson (pupil plane) beam combiner, and a scanning optical delay line is used to provide spectroscopic information and compensate for external delay





Single-Mode Mid-Infrared Fibers

- **Chalcogenide Fibers** (NRL)
  - A. Ksendzov et al., “Characterization of mid-infrared single mode fibers as modal filters,” Applied Optics 46, 7957-7962 (2007)
  - Transmission losses 8 dB/m
  - Suppression of 1000 for higher order modes
  - Useable to ~11 microns

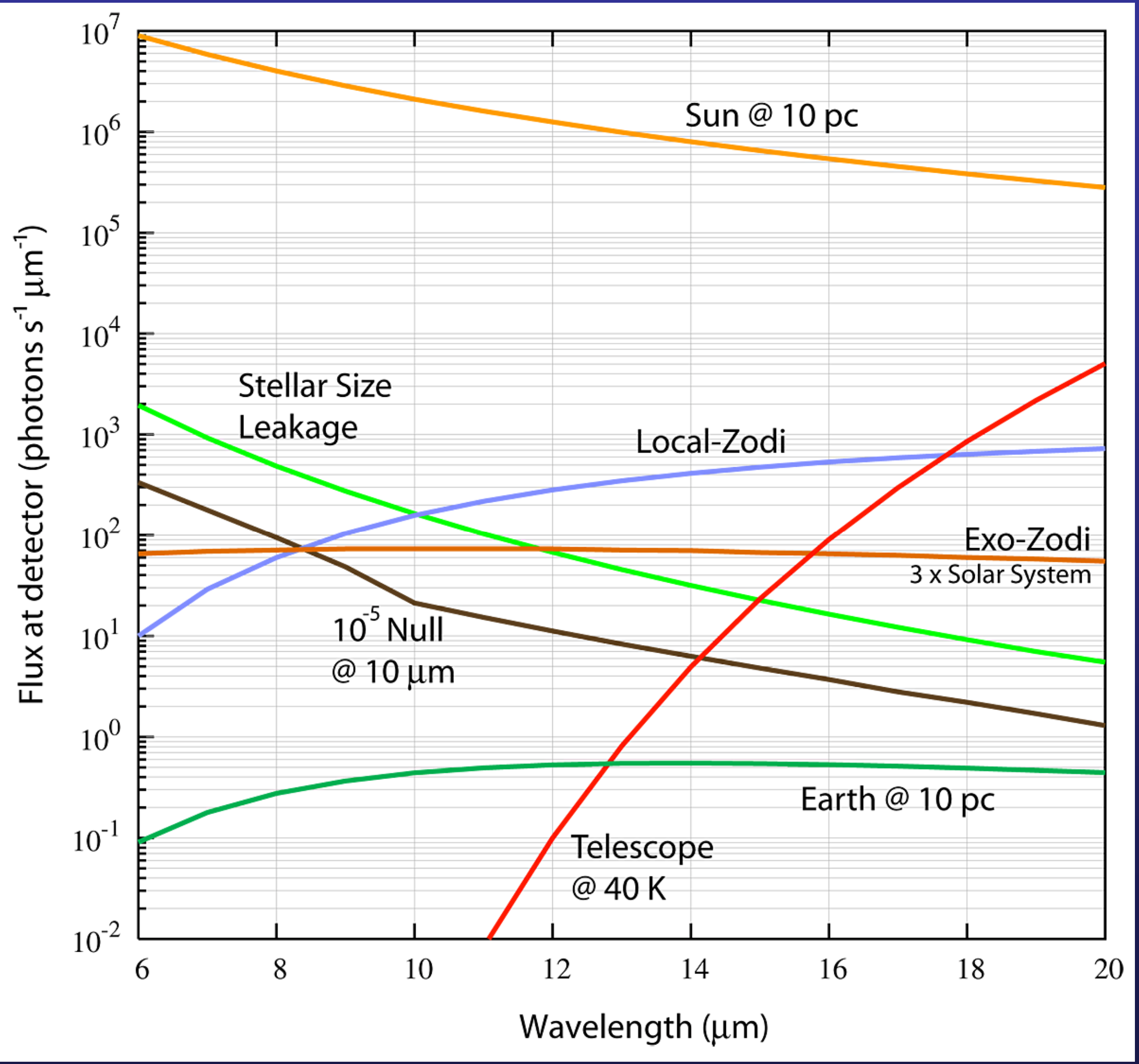


Example Chalcogenide Fibres, produced on contract by the Naval Research Laboratory

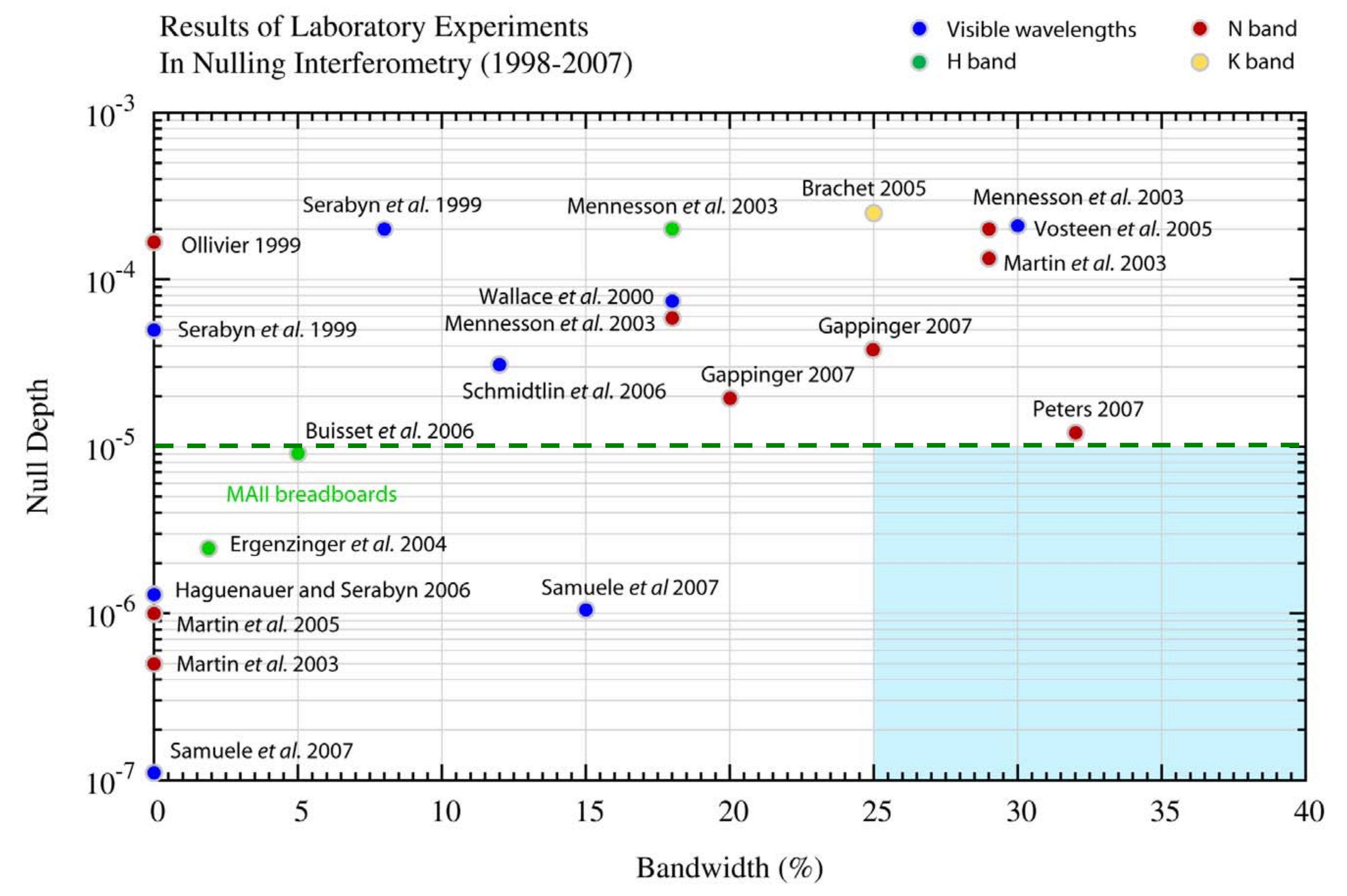
- **Silver-Halide Fibers** (Tel Aviv Univ)
  - A. Ksendzov et al. “Model filtering in mid-infrared using single-mode silver halide fibers,” Applied Optics, submitted.
  - Transmission losses 12 dB/m
  - Suppression of 16000 possible with a 10-20 cm fibre, with aperturing the output.
  - Useable to ~18 microns (?)

http://planetquest.jpl.nasa.gov/TPF-I/spatialFilters.cfm

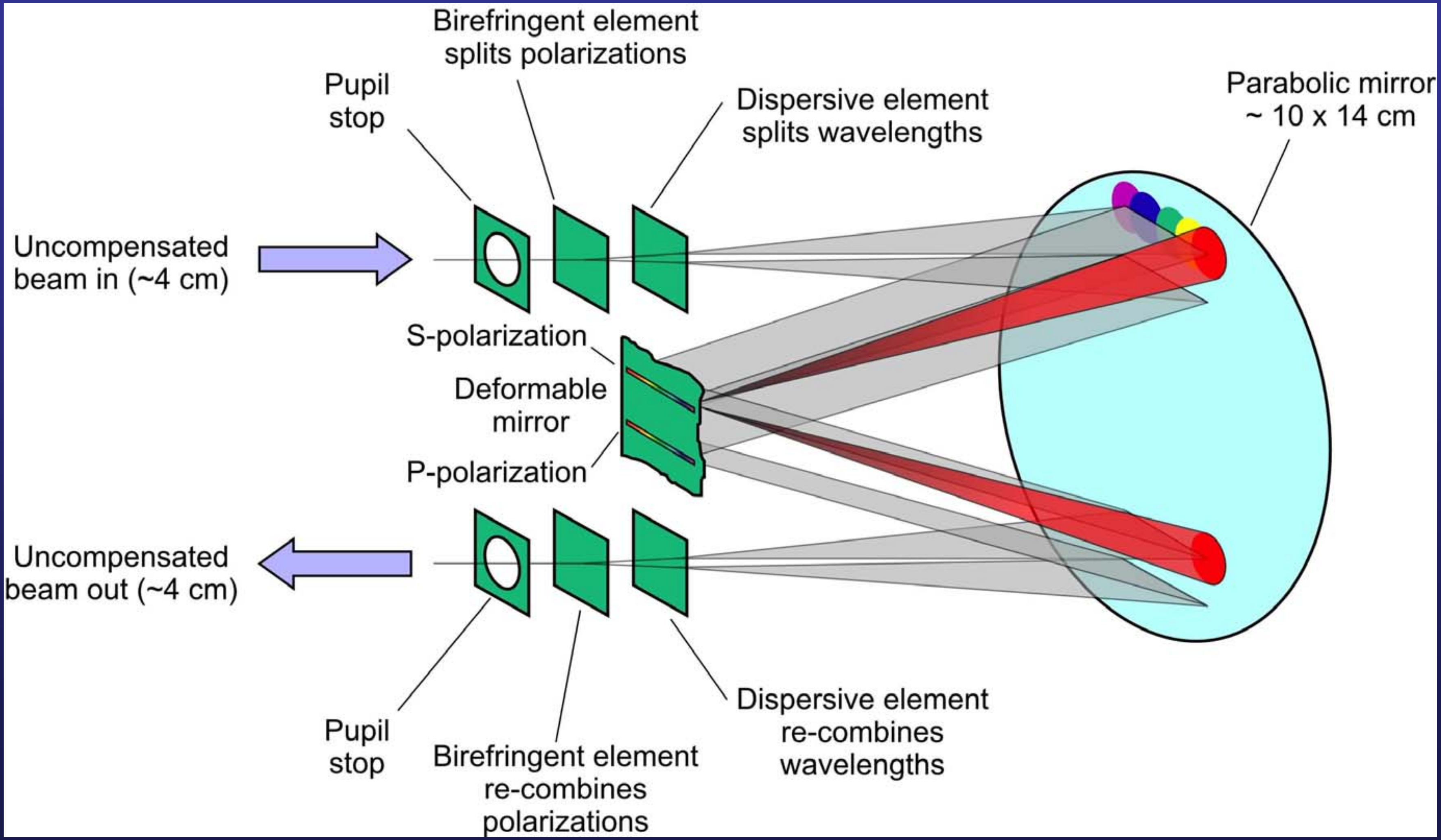
Sources of Noise at Mid-Infrared Wavelengths



State of the Art in Broadband Nulling



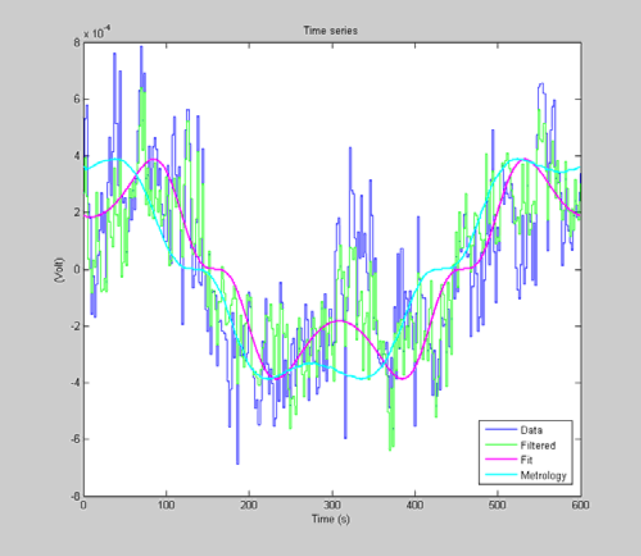
Broadband Starlight Suppression with a Deformable Mirror



Chopping, Averaging, Array Rotation

- **Planet Detection Testbed** (PDT)
  - Demonstrate array rotation, chopping, and averaging
  - Planet signal extraction with a 4-beam array
  - Planet signal < 10^{-6} relative to the star
  - Residual starlight suppression > 100.

Planet Detection Testbed

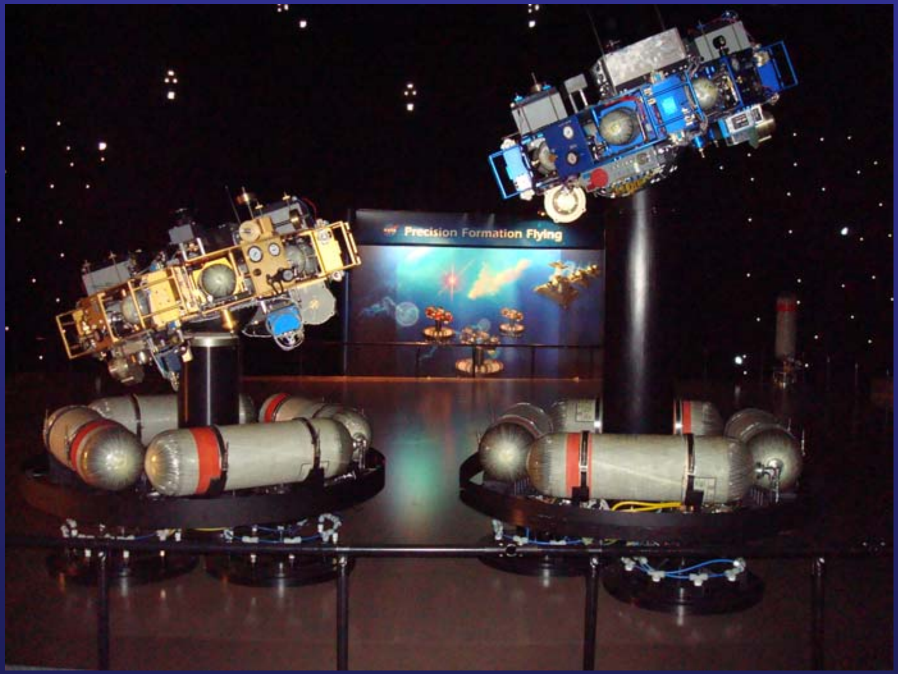


Planet signal extraction with the Planet DetectionTestbed: Planet signal 940,000 fainter than the star with null depth of 70,000 to 100,000. (Preparations for Milestone #4)

Technology for Formation Flying

Formation Control Testbed

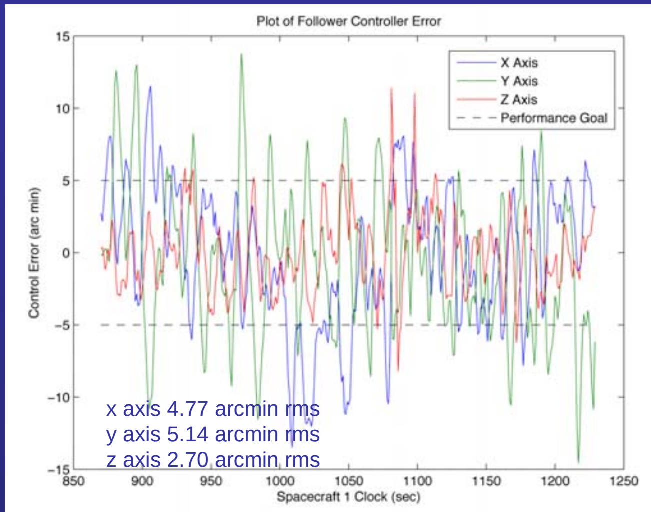
First vertical stage being integrated now in robot “Blue” (shown below) to provide 50 cm of vertical travel.

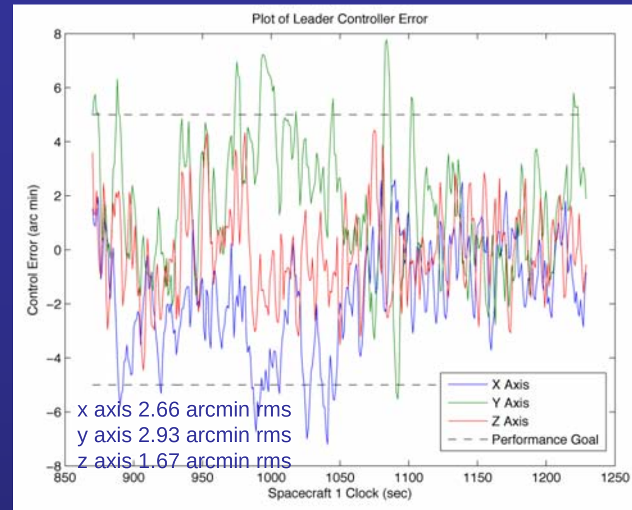


Second vertical stage to be delivered and installed in robot “Gold” in June 2008

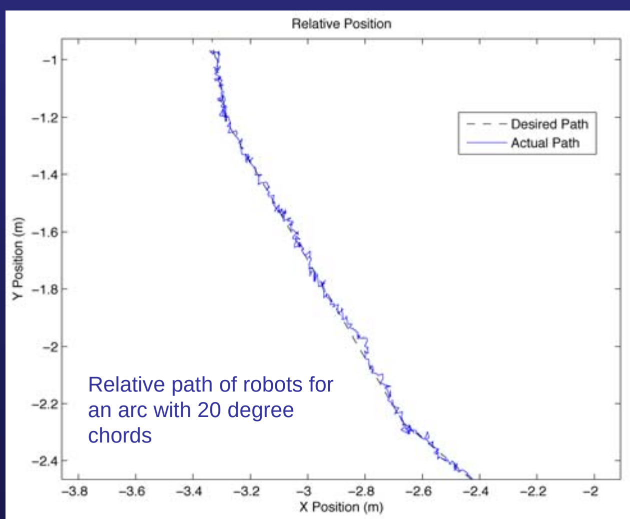
Phase I work ongoing for the Defence Advanced Research Projects Agency (DARPA)
F-6 Program: “Future, Fractionate, Fast, Flexible, Free-Flying - united by information exchange”

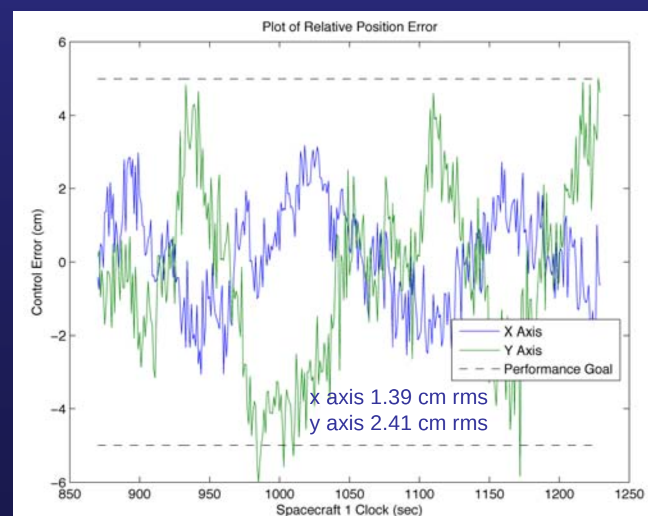
TPF-I Milestone #2: Formation Control Testbed





TPF-I Milestone #2 experiments for the formation precision performance maneuver were completed 30 September 2007





Goal:

Per axis translation control < 5 cm rms

Per axis rotation control < 6.7 arcmin rms

Demonstrated with arcs having 20 and 40 degree chords. Experiments repeated three times, spaced at least two days apart.

Milestone Report Published for 16 January 2008

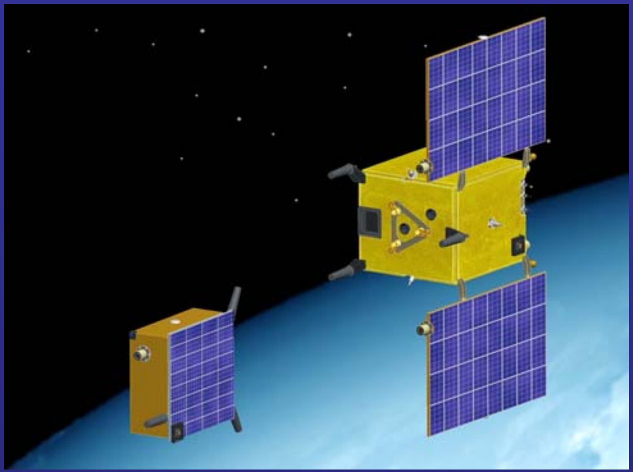
Example Milestone Data: Rotation maneuver with 20 degree chord segments

Overview of Formation Flying Efforts

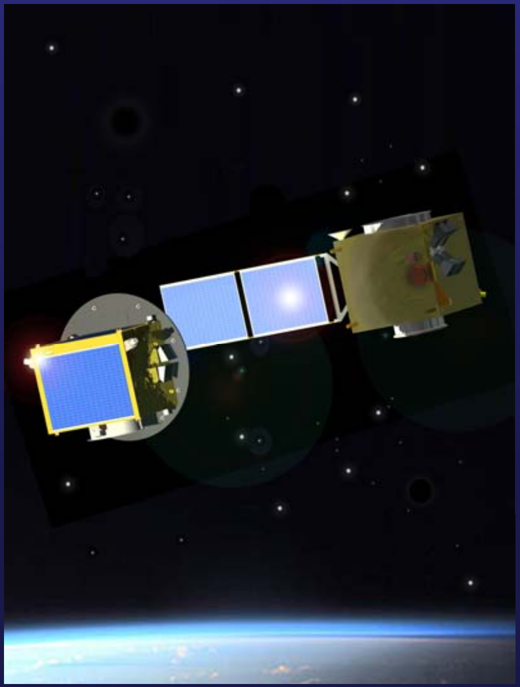
- **Orbital Express** (DARPA) May-July 2007
  - Demonstrated in-orbit servicing of satellites
  - Relative maneuvers of two satellites
  - Transfer of liquids and batteries

- **Autonomous Transfer Vehicle** (ESA) April 2008
  - Unmanned transport to the International Space Station
  - 10.3 m long and 4.5 m in diameter
  - GPS, video, and human supervision
  - Two days of demos, and rendezvous and docking
  - Exits to a destructive re-entry

Prisma (2009) and Proba-3 (2012)



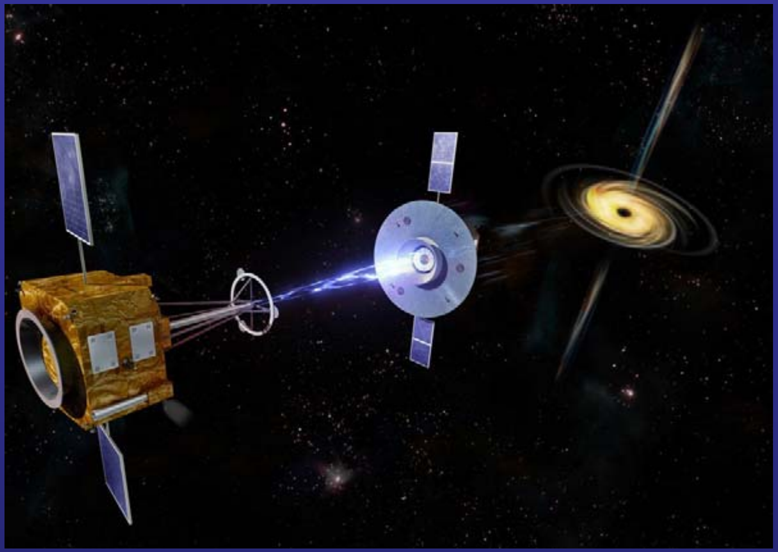
- **Prisma** (Swedish Space Corporation) June 2009
  - Rendezvous and docking demonstration
  - Prototype “Darwin” RF metrology
  - Precursor demonstrations for XEUS



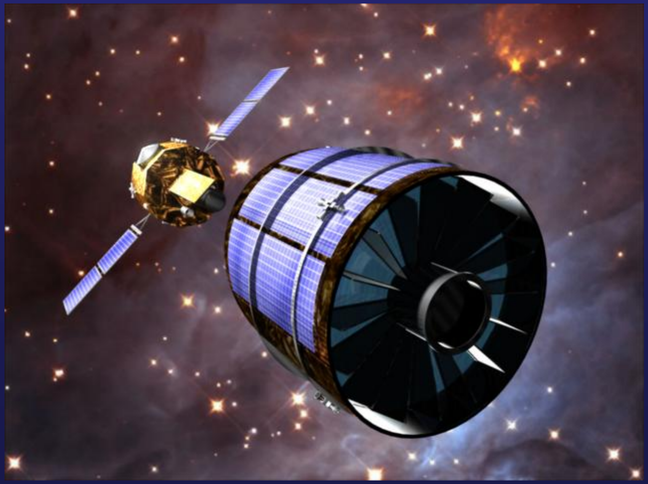
- **Proba-3** (ESA) 2012
  - Technology demonstration for XEUS
  - 30-150 m separation for demonstrations
  - Millimeter-level range control
  - RF Metrology & Optical metrology
  - Now in “bridging” Phase

Simbol-X (2014) and XEUS

- **Simbol-X** (CNES, ASI) 2014
  - X-ray telescope
  - 20-m separation of satellites
  - cm-level range control
  - Entering Phase B in summer 2008



- **XEUS** (ESA) Proposal for 2018 launch
  - X-ray telescope
  - 30-m separation of satellites
  - Millimeter-level range control



System F-6 (DARPA)

- **F-6 Objectives** (DARPA) 2012
  - Future, Fast, Flexible, Fractionated, Free-Flying
  - Each spacecraft modules on a smallsat/microsat scale (300 kilograms wet mass).
  - First launch shall be planned to occur within four years of program start (ie. 2012).
  - Modules may be distributed across multiple launches. The launch vehicle(s) required shall be commercially available, manufactured in the US, and have demonstrated at least one successful previous launch.
  - The on-orbit lifetime design of the system shall be at least one year after the launch of the final spacecraft.
  - All designs should retain a fault tolerant strategy that limits the effects of single part failures on the ability to command each spacecraft, as well as to limit any navigational threats during cluster operations (e.g. a thruster inadvertently stuck open).

- **Phase I Contracts awarded to**
  - Boeing Co.
  - Lockheed Martin Space Systems Co
  - Northrop Grumman Space and Mission Systems
  - Orbital Sciences
- **Phase II reduces to two contractors**
- **Phase III and IV to a prime**

Some Conclusions

Technical Readiness for a Small Structurally Connected Interferometer

Item	Description	TRL	Notes
1	Cryocoolers	6	Source: JWST
2	Precision cryogenic structure (booms)	6	Source: JWST
3	Detectors (near-infrared)	6	Source: HST, JWST Nircam
4	Detectors (mid-infrared)	6	Source: Spitzer IRAC, JWST MIRI
5	Cryogenic mirrors	6	Source: JWST
6	Optical fiber for mid-infrared	4	Source: TPF-I
7	Sunshade	6	Source: JWST
8	Nuller Instrument	5	Source: Keck Interferometer Nuller, TPF-I project, LBTI
9	Precision cryogenic delay line	6	Source: ESA Darwin

*Note: The requirement for the FKSI project is a null depth of 10^{-4} in a 10% bandwidth. Laboratory results with the TPF-I testbeds have exceeded this requirement by an order of magnitude (Lawson et al. 2008).

Technology Development for the Large Mission

- Some additional work needs to be done on the warm testbeds to get to 10^{-5} null depth requirement, but we are quite close (about 20% above the requirement).
- Cryogenic testing of optical fibers
- Formation flying demonstrations in space

Research & Analysis Recommendations

- ***Ground-based interferometry***
  - ***Ground-based interferometry serves critical roles in exoplanet studies. It provides a venue for development and demonstration of precision techniques including high contrast imaging and nulling, it trains the next generation of instrumentalists, and develops a community of scientists expert in their use.***
  - ***We endorse the recommendations of the "Future Directions for Interferometry" Workshop and the ReSTAR committee report to continuing vigorous refinement and exploitation of existing interferometric facilities (Keck, NPOI, CHARA and MRO), widening of their accessibility for exoplanet programs, and continued development of interferometry technology and planning for a future advanced facility***
  - ***The nature of Antarctic plateau sites, intermediate between ground and space in potential, offers significant opportunities for exoplanet and exozodi studies by interferometry and coronagraphy.***
- ***Space-based Interferometry***
  - ***Space-based interferometry serves critical roles in exoplanet studies. It provides access to a spectral range that can not be achieved from the ground and can characterize the detected planets in terms of atmospheric composition and effective temperature. Sensitive technology has already been proven for missions like JWST, SIM, and Spitzer, and within NASA's preliminary studies of TPF***

More Recommendations on R&A Support

- ***Theory support:***
  - ***We will require sustained support of strong astrobiology and atmospheric chemistry programs.***
- ***Agency Coordination & Programmatic Strategy***
  - ***NASA and NSF goals, makes it an ideal topic for coordination between the agencies, and we urge NASA and NSF staff to leverage this relationship to cover the full breadth of exoplanet science and technology***
- ***International Coordination, Collaboration, & Partnership***
  - ***The relationships forged between US and European collaborators should be fostered during the next decade for further studies of small mission and flagship mission concepts. A new letter of agreement is necessary to further future collaborations.***